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X-Ray detectors in astronomy

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Abstract. The developments in the field of X-ray detectors used in astronomy are described here. A brief sketch of the historical developments is given, with particular emphasis on the efforts made in the Indian context. Results obtained from a balloon borne hard X-ray telescope and the Indian X-ray Astronomy Experiment are also highlighted.

Keywords : X-Ray spectra, instruments, black holes, accretion

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1. Introduction

X-ray astronomy is an important branch of the "space age" astronomies where one necessarily needs a space probe to go above the Earth's atmospheric blanket to make astronomical observations. In Figure 1 the thickness of this atmospheric blanket (given in kms as well as fraction of atmosphere) at which radiation gets attenuated by half, is given as a function of frequency. It can be seen from the figure that apart from radio and optical, almost all other wavelengths are absorbed by the atmosphere and space probes are required to study cosmic objects in these wave-bands. Each wavelength band has its own length scale (comparable to the wavelength) and the temperature range it probes (assuming a Planckian blackbody distribution) and these are also shown in the figure. The X-ray range probes the atomic dimensions and it pertains to very high temperatures ($> 10^6$ K).

After the serendipitous discovery of the first non-solar X-ray source in 1962 (Giacconi et al. [1]), the field of X-ray astronomy has rapidly evolved as a major tool in astrophysics. It is particularly suited to study violent and non-thermal phenomena which are very prevalent in various astrophysical sites. Any accelerating site will be revealed by their X-ray emission because accelerated electrons are efficient radiators due to their low mass and they generally emit electromagnetic radiation close to their rest mass, which is the X-ray wave-

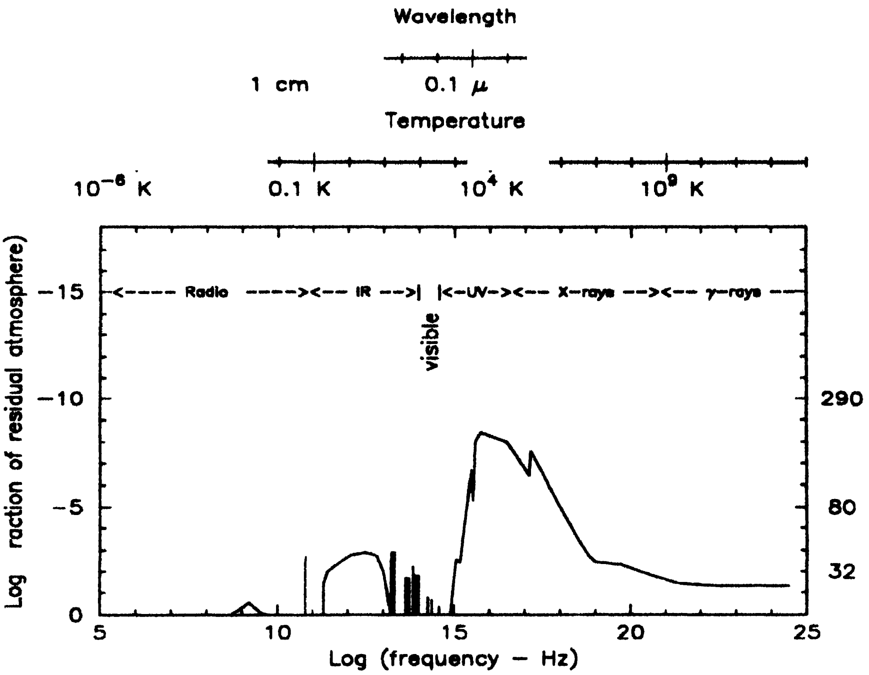

Figure 1. Fraction of atmosphere at which electromagnetic radiation gets attenuated by half is given as a function of frequency. The corresponding altitude (in kms) is given in the right hand scale (Charles and Seward [4]). The wavelength and equivalent blackbody temperature are also shown in the figure.

band. Further, these accelerated electrons thermalise in the ambient medium, which emits radiation near the characteristic atomic transition lines in the X-ray region. Hence the X-ray waveband gives information on the acceleration sites and the ambient medium.

Developments and innovations in the X-ray detection technology has proved to be an important factor in the spectacular growth of X-ray astronomy that has occurred in the past three decades. In this paper these developments will be traced, with particular emphasis on efforts made in the Indian context. Fraser's [2] book on the same subject gives a detailed description of the X-ray detectors used in astronomy. Some of the historical aspects touched here is described in detail by Tucker and Giacconi [3] and a general introduction to the subject of X-ray astronomy can be found in Charles and Seward [4].

2. Historical Perspectives

The initial development of X-ray astronomy is closely related to the post Second World War scientific revolution that occurred in astronomy. The precursors for this revolution can be traced to the following developments.

1. The Naval Research Laboratory (NRL) was established in USA in 1924 with an explicit mandate of exploiting the newly discovered radio waves for communications. This led to new techniques in radio detection and several discoveries in radio-astronomy were possible like supernova remnants (SNR), Active Galactic Nuclei (AGN), Cosmic Microwave Background Radiation (CMBR) and radio pulsars.

2. Captured German V-2 rockets were made available to the scientific community in USA, immediately after the Second World War. In a series of rocket flights, pioneered by H. Friedman of NRL, it was found that a) Sun emits X-rays $T \sim 10^6$ K, b) X-ray to optical flux ratio $F_x/F_o \sim 10^{-7}$, c) X-ray emission strongly enhances during solar flares.

3. The dream-like success of the Soviet space program lead to the launch of Sputnik 1 of weight 83.6 kg on Oct 4, 1957. Within two months Sputnik 2 of weight 500 kg was launched and in the next six months Sputnik 3 of weight 1327 kg was launched. A direct consequence of this was the establishment of NASA in the USA as a civilian organization which resulted in a vast amount of resources getting diverted into fundamental science (as compared to military science). The enormous funds available helped boost space technology which resulted in the spectacular growth of several branches of space astronomy.

Several organizations were actively participating in executing NASA contracts, one of them is the American Science & Engineering (AS&E). The motivating force behind this company is R. Giacconi. Giacconi, who can be called as the 'grand-father' of X-ray astronomy, was influenced by the famous cosmic ray physicist Bruno Rossi who had "*a deep-seated faith in the boundless resourcefulness of nature, which so often leaves the most daring imagination of man far behind*" [3].

Giacconi wanted to exploit the new opportunities that are available in the space platform for scientific purposes. Since X-rays do not penetrate Earth's atmosphere, they were one of the natural choices. Extrapolating from the known X-ray flux of Sun, it is not expected to obtain any detectable X-ray flux from even the nearest star. He, however, wanted to make a rocket flight to measure X-rays coming from outside solar system but the proposal was rejected by NASA. The proposal was resubmitted to Air Force with the additional aim of detecting X-rays from Moon and it was accepted. A bright new X-ray source - Sco X-1 - was discovered in the rocket flight of June 18, 1962. The brightness of this source far exceeded any theoretical expectations and a whole new field of X-ray binary sources involving compact objects as central engines opened up.

Meanwhile, Giacconi had ambitious programs for X-ray astronomy in as early as 1963. These included rocket studies, modest orbiting Solar Observatories, X-ray Explorer satellites, a small focusing X-ray telescope and a large X-ray telescope. The X-ray explorer SAS-1 (also called *UHURU*, which means freedom in the Swahili language) was launched from San Marco, Kenya on Dec 12, 1970. This is the first X-ray satellite and it was very successful in unraveling the mystery of X-ray stars.

As detector and telescope technology has matured, enormous progress has been made by a series of ever more capable X-ray astronomy missions. In 1978, the first sensitive X-ray focusing telescope, the Einstein Observatory, was launched and X-ray emission was detected from virtually every class of astronomical objects. Since then, several X-ray observatories have been launched which have made X-ray observations an indispensable tool to study any branch of astrophysics.

2.1. *The Indian context*

The exiting discovery-era of X-ray astronomy in the sixties saw strong Indian participation in terms of balloon as well as rocket borne observations. Tata Institute of Fundamental Research (TIFR) had an ongoing balloon programme for cosmic ray studies which could be effectively used for hard X-ray astronomy. A group at Physical Research Laboratory (PRL) also conducted several balloon flights for hard X-ray astronomy. Intensity variations in bright hard X-ray sources and energy spectra of cosmic X-ray background are some of the interesting results obtained from these observations [5-6].

In the field of rocket based X-ray astronomy, India made early strides starting from the launch of two rockets carrying proportional counter based payload made by PRL for the measurement of intensity and energy spectra of soft X-ray sources [7]. Compared to these the Indian efforts in the satellite based X-ray astronomy is quite modest: the first Indian satellite Aryabhatta launched in 1975 carried proportional counters of area 60 cm^2 and later the Bhaskara satellite carried an X-ray pin hole camera. During the rapid strides made in X-ray astronomy, particularly by the use of focusing techniques, the Indian efforts are mainly confined to balloon studies. This is due to the lack of a robust Indian satellite launch systems and also due to the ever-increasing technological gap between India and the Western countries which was prevalent in the "Cold-war" era.

3. X-ray detection principles

The development of X-ray astronomy is closely linked with the developments in the X-ray detection techniques. The first rocket flight carried a small area proportional counter and crystal detectors have been used for hard X-ray astronomy on balloon platforms. Larger size and efficient background reduction techniques are the early improvements, which was used in the *UHURU* satellite. X-ray focusing technique is the next major development which was used in the Einstein observatory.

X-rays are highly ionizing electromagnetic radiation. When an X-ray photon interacts in a medium, it transfers its energy abruptly to an electron. Since the X-ray interaction is on individual atoms/ electrons, they are probabilistic in nature. They interact via photo-electric effect, Compton scattering or pair production (for gamma-rays). For X-ray energies, photo-electric effect is predominant. Unlike α and β particles which undergo continuous interaction (where the concept of range of interaction is meaningful), X-rays undergo point interaction and hence cross-section for interaction is the relevant parameter. X-rays transfer their energy abruptly to one or two electrons. These (fast) electrons ionize or excite the medium. X-ray detectors measure these secondary electrons from ionisation or the secondary photons from de-excitation.

Proportional counters and crystal detectors are commonly used as large area photometric detectors. Proportional counters collect the primary ionisation using the high electric field near an anode wire with high voltage. To improve energy resolution, excitation property, rather than the ionisation property, of the noble gas can be used in gas scintillation proportional counters. The fluorescent properties of crystals are used and the resultant light emission is measured by photo-multiplier tubes.

For X-ray energies scattering and absorption are more predominant than reflection. If the energy of X-rays is low, for very low angles of incidence, total external reflection can take place. Such grazing incidence telescopes can be used in X-ray astronomy.

At the focal plane, X-ray images can be obtained by using suitable imaging detectors. Position sensitive proportional counters are one of the commonly used imaging detectors (resolution element $\sim$0.1 mm). For higher spatial resolution micro-channel plates can be used ($\sim$13 μ).

To measure the energy spectra of X-ray sources, detectors with energy resolution better than proportional counters may be required. Good energy resolution X-ray detectors can be made in small size and they can be used at the focus of an X-ray telescope. Semiconductor detectors or CCDs can be used. New detector concepts like bolometers are currently under development.

4. X-ray telescopes

Atmospheric absorption, requirement of complex technology and the resultant long lead time are some of the constraints of making any space-borne experiments. The large cosmic-ray induced background, low signal from stellar sources and the limited band-width that is normally available are further constraints for X-ray observations. Two types of detection methods are traditionally used.

Large area detectors: To collect large number of photons a large area detector like proportional counter or scintillation detector are used. To get some idea of the source direction, some device to restrict or modulate the field of view like simple collimator or coded aperture masks are used.

Focusing detectors: For low energy X-rays nested mirrors can be used at grazing incidence. Appropriate detectors are used at the focus. The advantages of using focusing technique are tremendous: a) For a given collective are, detector area is very small and hence, innovative detectors with good energy resolution can be built, b) the small area of the detector results in low background, c) Since the X-ray direction is available, the background for the small solid angle of the source is very small and d) simultaneous background measurement is available. The advantages of focusing in X-ray astronomy is highlighted by sensitivity considerations.

Since X-rays detectors are individual photon counting devices, the uncertainty in measurement is simply the statistical error in counting. Large area photometric detectors are background dominated whereas focusing telescopes work as zero background detectors (because of lower detector area for a given collective area and small solid angle covered for the source detection). The minimum flux that can be detected at 3 σ confidence level (F_{min}) can be written as

$$F_{min} = 3\sqrt{\frac{B_D\Omega + B_i}{A\epsilon t\delta E}}$$

for large area detectors, and for focusing detectors

$$F_{min} = \frac{9}{A\epsilon t\delta E}$$

where B_D is the cosmic diffuse X-ray background flux, B_i is the internal background, A is the photon collection area, ϵ is the detector efficiency, δE is the energy range, Ω is the solid angle subtended by the field of view and t is the duration of observation. The scope for improving the sensitivity in focusing detectors is very high because it goes as the inverse of area and duration (rather than the square root of these parameters). Focusing can be done mainly in low energies hence the improvement in the sensitivity of hard X-rays (> 12 keV) is very limited.

The improvements in the sensitivity of X-ray telescopes is put in perspectives along with those in the radio and optical wavebands in Figure 2. In the figure the spectrum of Crab nebula is shown as a function of frequency along with the bright quasar 3C 273 and a hypothetical quasar at a red-shift of 4 (shown as a dashed line). The Crab nebula is just visible to detectors flown on the first rocket flight (R); a 3 orders of magnitude improvement is achieved by the UHURU satellite (U); another 3 orders of magnitude improvement in

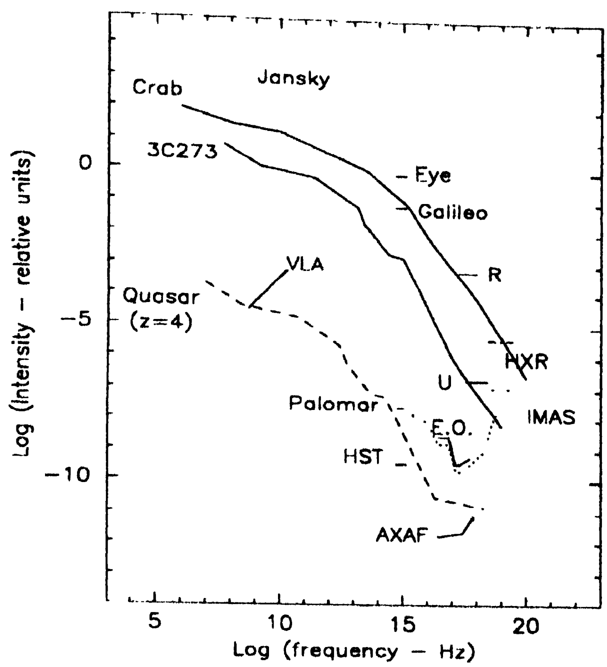

Figure 2. The sensitivity of telescopes used in various electromagnetic wavebands (based on a figure by R. Giacconi).

sensitivity is brought about by focusing techniques in the Einstein Observatory (E.O.); the advantages of X-ray mirrors are to be further exploited by AXAF. The sensitivity improvement in the hard X-ray band (HXR - shown as dash-dot lines in the figure) is just about 2 orders of magnitude. The proposed Indian experiment IMAS exploits the advantages of wide bandwidth. The more than 8 orders of magnitude improvement brought about in X-ray telescopes compares very favorably with that achieved in the radio and the optical wavebands. The Crab nebula is invisible to the first radio telescopes used by Jansky in 1930s and the current radio telescope VLA is better by a factor of 10^7, but the farthest quasars are barely visible. In the optical band the human eye can barely see the Crab nebula but a Galilean telescope can comfortably see it. The Palomar telescope and the HST signify an improvement of further 5 to 7 orders of magnitude.

The Indian efforts for the past two decades had to be confined to balloon payloads and small scale satellite payloads. Here I will describe two such efforts where I was personally involved.

4.1. *A balloon borne hard X-ray telescope*

The focusing technique is quite inefficient at energies above 12 keV (the hard X-ray band) because at these energies the wavelength of X-rays ($< 1\mathring{A}$) is comparable to the atomic dimensions. The importance of making observations in the hard X-ray band need hardly be stressed because this is the energy range where most of the signatures of non-thermal accelerating mechanisms are evident. The only way to have high sensitivity hard X-ray detectors is by making large area low background detectors, still the improvement in sensitivity is about an order of magnitude (see Figure 2). An attempt was made at TIFR to fabricate a good spectroscopy detector using a xenon filled hard X-ray telescope for a balloon platform.

The X-ray telescope consists of two Xenon filled Multi-cell Proportional Counters (XMPC) of area 1200 cm^2 each. The detectors are filled with a mixture of xenon, argon and methane gases and it has a detection efficiency of about 50% and energy resolution of about 13%. The field of view (FOV) of the detectors is defined by a passive tin-copper graded collimator to $5° \times 5°$. The response matrix of the detectors were calculated using a Monte-Carlo routine and the systematic errors in the data are brought down to a very low level [8-10]. Several interesting results were obtained using this telescope and results obtained on the black hole candidate Cygnus X-1 is briefly described here.

Cygnus X-1 is one of the brightest X-ray sources in the sky. It is a binary with one companion identified to be a normal star and the other 'invisible' compact companion is thought to be a black hole. It shows two distinct spectral states, 'low' and 'high', depending on its soft X-ray flux. Rapid and chaotic intensity variations over time scales of milliseconds to several seconds have been seen from this source and such variations have been conventionally taken as one of the indicators of the existence of black holes [11]. Since its spectral state remains relatively stable for long durations (days to years) data from different observatories obtained at different epochs can be compared with each other. Further, since the source is very bright, measurable flux is available at all the energies to sufficiently constrain the energy spectrum.

Most of the attempts so far to explain the energy spectrum of Cyg X-1 were over limited dynamic range and even when data over wider band-widths were used, they were generally from detectors of poor energy resolution. The accretion theories, however, make definitive predictions regarding the energy spectrum. To understand the nature of the underlying X-ray continuum in this source it is necessary to have good energy resolution at lower energies, wider band-width at higher energies, and medium energy resolution at the intermediate (20 – 100 keV) energies. This has been achieved by combining data from various international observatories. The low energy data has been obtained from the European satellite EXOSAT and the high energy data from the OSSE detector of the Compton Gamma-ray Observatory. There is a dearth

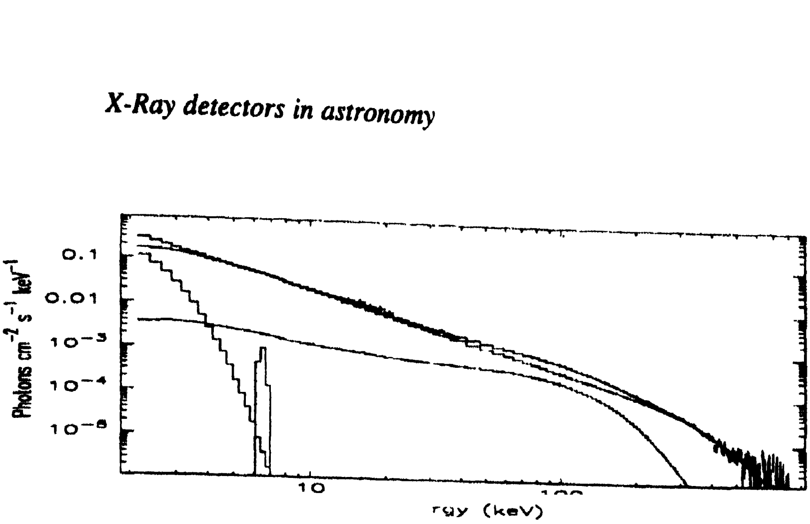

Figure 3. The deconvolved spectra of Cygnus X-1 obtained from the European satellite EXOSAT, balloon-borne payload XMPC and the OSSE detector onboard the CGRO observatory are shown. Contributions from individual model components (low energy blackbody, Gaussian line and two Comptonisation components are shown separately as histograms [10].

of good quality data at the intermediate energies and this has been bridged by the XMPC data.

A simultaneous fit to the wide band data of Cyg X-1 pertaining to the low state of the source was attempted. A statistically acceptable fit to the wide band (2 – 500 keV) X-ray spectrum of Cyg X-1 was obtained. The best fit spectral model consists of a soft excess modeled as a blackbody emission, characteristic iron line and a continuum consisting of two Sunyaev-Titarchuk inverse Compton models (CompST). The deconvolved spectrum is shown in Figure 3 along with the contribution from the individual model components. Chakrabarti & Titarchuk [12] have predicted the X-ray spectrum emitted from accretion disks around black holes and the various components in the model agrees quite closely with these predictions [10].

4.2. *Indian X-ray Astronomy Experiment (IXAE)*

When the Indian satellite launch capabilities made a major leap in the nineties by the development of the Polar Satellite Launch Vehicle (PSLV), the available opportunity was effectively exploited by a collaborative experiment between TIFR and ISRO in the launch of the Indian X-ray Astronomy Experiment (IXAE). This experiment is a part of the Indian Remote Sensing satellite (IRS - P3), which was launched by the third developmental flight of the Polar Satellite Launch Vehicle (PSLV-D3) on 1996 March 21 from the SHAR range, India. The payload includes three pointed proportional counters (PPC) each with an area of 400 cm^2 and an opening angle of 2°× 2°. The detectors are sensitive to X-rays of energy range 2 to 20 keV. The payload also includes an

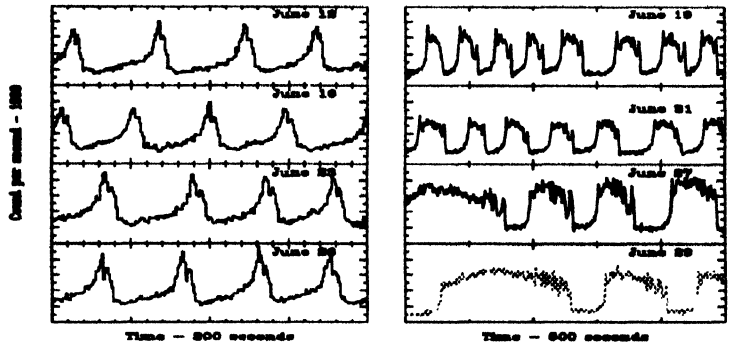

Figure 4. The regular (left panel) and irregular (right panel) bursts observed in GRS 1915+105 with one of the PPCs. Date of each observation is given in the respective panels.

X-ray Sky Monitor [13].

Though IXAE is modest compared to the observatory class satellites that are in operation, it was effectively used to obtain very valuable data on several bright Galactic binary X-ray sources like the black hole candidate sources Cygnus X-1 and GRS 1915+105 and several slow X-ray pulsars [14]. Some interesting results obtained on GRS 1915+105 is described here.

GRS 1915+105 was discovered in 1992 with the WATCH all sky X-ray monitor on-board the GRANAT satellite [15] During the two years of hard X-ray observations by WATCH, two powerful outbursts were discovered and during the peak of the outbursts the source luminosity was as high as 10^{39} erg s^{-1}. Superluminal motions of two symmetric radio emitting jets of GRS 1915+105 were discovered by Mirabel & Rodriguez [16]. Correlated enhanced radio and X-ray emissions were discovered from the source with a near simultaneous monitoring over a long period [17-18]. This source shows a variety of X-ray states like the 'bright state', 'chaotic state', 'flaring state' and the 'low-hard' state. Since the only intrinsic parameter that must be changing in the various states is the mass accretion rate, this source, in recent times, has proved to be a laboratory in the true sense of the word.

X-ray observations of GRS 1915+105 using IXAE were carried out from 1997 June 12 to June 29 in the energy range of 2–18 keV and revealed the presence of persistent quasi-regular bursts with different structures (Figure 4). Only one of the three types of bursts is regular in occurrence revealing a stable profile over extended durations. The regular bursts have an exponential rise with a time scale of about 7 to 10 s and a sharp linear decay in 2 to 3 s. The X-ray spectrum becomes progressively harder as the burst evolves and it is the hardest near the end of the burst decay. It was proposed that the sharp decay in the observed burst pattern is a signature of the disappearance of matter through the black hole horizon [19].

Yadav et al. [20] made a detailed study of the various types of X-ray bursts seen in GRS 1915+105. They presented a comprehensive picture for the origin of these bursts in the light of the recent theories of accretion disk. It was suggested that the peculiar bursts are characteristic of the change of state of the source. The source can switch back and forth between the low-hard state and the high-soft state near critical accretion rates in a very short time scale, giving rise to the irregular and quasi-regular bursts. The fast time scale for the transition of the state is explained by invoking the appearance and disappearance of the advective disk in its viscous time scale. The periodicity of the regular bursts is explained by matching the viscous time scale with the cooling time scale of the post shock region. Such fast spectral changes were also confirmed by Rao et al. [21].

Since the canonical spectral states of black hole binaries remain for considerably long duration (upto years) in the same state with similar properties, it is usually assumed that they are some stable solutions for the accretion disk. It is normally believed that for a given source the total accretion rate is the governing parameter for the spectral changes. The fact that the source makes very fast repeated state transitions, implies that the two solutions for the accretion disk (corresponding to the two spectral states) must exist for roughly the same total mass accretion rate because the time scale of the state change ($\sim$10s) observed during the irregular bursts is much smaller than the time scale for the readjustment of the accretion disk for any global mass accretion rate changes. Hence two solutions for the accretion disk must exist for the same global accretion rate, which essentially reinforces the Two Component Accretion Flow model of Chakrabarti [22].

5. Future X-ray telescopes

EXOSAT, Ginga, ROSAT, and ASCA satellites have laid the foundation for X-ray astrophysics. These endeavors will climax with the launch of the Chandra (formerly AXAF), XMM, and Astro-E missions. The future instruments mainly emphasize on large collective area, extremely good energy resolution etc.

A wide band X-ray telescope with good sensitivity and energy resolution will be extremely useful for the X-ray spectral studies. With such an aim the Indian Multi-wavelength Astronomy Satellite (IMAS) has been proposed. The heart of the telescope will be a Large Area Xenon-filled Proportional Array Counters (LAXPAC) with a total area of 6000 cm^2. These will be high pressure xenon filled proportional counters giving a good energy response (2 – 80 keV) and reasonable energy resolution. A focusing Soft X-ray Telescope (SXT) with conical mirrors but with modest area (200 cm^2) and good energy resolution (X-ray CCD) will provide complementary data at low energies. An X-ray Monitor (XRM), which is proportional counter based, will be very useful to track ~ 100 bright X-ray sources with good sky coverage ($\sim \pi$ str.). Concurrently a wide field of view UV Telescope (UVT) of 50 cm diameter mirror will give very useful information on astrophysical sources. Several institutes across India have taken up responsibility of making some part of the payloads and this dedicated satellite is planned to be launched in the first half of the first decade in the next century.

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